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This report results from a contract tasking Claredon Laboratory as follows: The contractor will construct a CW dye laser that functions as a master oscillator. The output of the oscillator will be locked to a relevant sodium line and will be broadened to efficiently excite mesopheric sodium. In order to co ct this oscillator the contractor will design and construct an atomic sodium frequency lock and investigate schemes for line broadening of the output.

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Report on Special Contract No. SPC-95-4051

Design of an atomic Sodium frequency lock for the dye master oscillator of a sodium laser guide star

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A CW laser master oscillator for a scalable sodium laser guide star: General issues

Summary

A dye master oscillator (DMO) suitable for incorporation into our sodium laser guide star (LGS) system has been successfully designed and constructed. An atomic sodium frequency lock has been designed, evaluated and implemented to give long term frequency stability of ±0.5 MHz over periods of many hours (>7.5 hours). Computer modelling of electro-optic phase modulator operation has allowed us to assess different drive regimes, and consideration of both standing wave and travelling wave devices has revealed the most suitable of those currently commercially available, as well as those expected to be obtainable in the relatively near future, and allowed us to purchase a device for evaluation.

Consequently the DMO has been assembled together with the other components of our sodium LGS system to allow the detailed evaluation of many aspects of its design, including beam quality, preservation of spectral content and pump power conversion efficiency as well as to investigate pulse multiplexing strategies.

Introduction

This programme of research was undertaken as a part of an ongoing project to investigate a number of the issues related to the construction of a scalable sodium laser guide star (LGS) system for use with astronomical adaptive optics. In this application it is necessary to construct a laser system, the output of which displays a number of characteristics. The output must be accurately tuned to one of the sodium resonance lines, and while having an average output power in the range of tens to one or two hundred Watts, the peak power must be carefully limited such that the sodium saturation intensity is not exceeded in the mesospheric sodium layer spot. In addition, the beam quality must be sufficiently good that the guide star spot of sufficiently small diameter to be effectively a point source at the resolution of the adaptive optics wavefront sensor sub-aperture.

Despite much effort in computer modelling of the predicted photon returns from a given LGS system, uncertainties and variations in many of the parameters have rendered these incapable of predicting with a high degree of certainty the optimum average power level required from a sodium LGS system for a given combination of telescope, observation wavelength and site. For this reason we have chosen to design our laser system on a modular, scalable basis, such that at any point the output average power can be increased by the addition of further modules, though without any increase in the output peak power. This last criterion is vital if the photon returns are to increase linearly with the average power and module number.

In order to accomplish this we have opted for time multiplexing of low duty cycle, high repetition rate pulse trains, such that each module, or sub-unit, generates an individual pulse train, separated in time by a delay with respect to all others. In this way, by means of suitable hardware, a composite output can be generated consisting of the sequential combination of all the pulse trains. The incorporation of additional sub-units, therefore, contributes to the average power by adding more pulses to the train, though without increasing the maximum peak power.

The spectral output of each sub-unit has the same requirements in terms of centre wavelength and bandwidth in order to make optimum use of the mesospheric sodium transition Doppler linewidth. It is critical that the centre frequency is maintained at the peak of the local peak of the transition over the period of an extended operation run which might typically be 8 - 10 hours or more. In order to minimise hardware and power requirements as well as cost it is desirable that the necessary frequency locking and linewidth broadening be performed upon a single master oscillator unit that can be exploited by all sub-units, rather than on each one individually. For it to be possible to synchronise this with an arbitrary number of high pulse repetition frequency (prf) pulsed sub-units this master oscillator must operate continuous wave (CW).

We undertook, therefore, to construct such a CW master oscillator the output of which was to be locked in a stable reliable way to the peak of the appropriate sodium transition. The output was to be effectively broadened in linewidth (on the timescale of the sodium upper state lifetime - 16ns) before being pulse amplified in a

manner ensuring maintenance of high beam quality and bandwidth, and maximum efficiency of conversion of pump power.

CW Master Oscillator construction

Owing to the very limited funds available to this project the technology available from which to construct a CW master oscillator that could be tuned to the wavelength of interest was that of an Argon ion laser pumped CW dye laser. The Argon ion laser was obtained as a used, non-operational Spectra-Physics Model 168, 5W unit for which we would require to replace the plasma tube. The dye laser was a Coherent Model 599-21 device on loan from another group within the Clarendon Laboratory for which we would be required to obtain some cavity optics for the wavelength at which we would be operating as well as, potentially, some additional refurbishment.

The (professional) replacement of the plasma tube in the Argon ion laser was accomplished and a pump, heat exchanger, reservoir, flow meter, particle filter, and other components were purchased and a closed loop cooling system with water to water heat exchanger was constructed.

Unfortunately, as a result of the fact that we were constrained to using a refurbished, used device we had a series of failures of the Argon ion laser which resulted in a number of significant delays to our investigation. The sequence of failures is described in Appendix A.

We were, however, finally left with a pump laser that gave the full specified power, in TEM_{00} mode, with which to pump the dye laser, however the combination of time spent waiting for repairs and servicing to be performed and replacement parts to be obtained and attempting to use a device that we believed to have been fixed but was still unable to achieve specifications had caused us considerable loss of time.

The CW dye laser on loan to us from another group within the Clarendon Lab caused us considerably less difficulty than the Argon ion laser, however a significant amount of work was still required to render it usable.

Both the high reflector and the tweeter (turning mirror mounted on a piezo-electric stack) had to be replaced with components with the necessary coatings for 590 nm operation. The circulator tubing was all replaced, as well as many of the

fittings. Finally thorough cleaning of the intracavity optics and a complete, ground up realignment of the entire system were necessary to attain the specified performance.

The frequency lock

Once the individual components of the dye master oscillator (DMO) had been individually commissioned and mutually aligned it was possible to address the issue of spectral stability. The Coherent 599-21 laser uses a temperature controlled reference cavity to provide short term frequency stabilisation, however the long term drift is specified as <100 MHz/hr. As the requirement for a sodium LGS system, if it is to generate maximum photon returns, is of the order of <10 MHz over the course of a full night's operation, of perhaps 8 - 10 hrs, it was clear that an additional frequency lock would be required.

It was decided to employ a frequency lock design that incorporated an atomic sodium sample in order to ensure a correct wavelength reference to the transition of interest. In order to achieve the required wavelength precision it was necessary to employ a Doppler free spectroscopic technique. In addition it was desirable to avoid having to introduce a wavelength modulation into the output of the dye laser, a pre-requisite for many frequency lock techniques in order to maintain the lock point. It was decided to investigate an implementation of the Polarization Spectroscopy technique. This we found to be extremely successful, allowing us to lock to ±0.5 MHz for periods of 7.5 hours. A full report on the details and results of this study is enclosed separately.

Manipulation of bandwidth

In addition to maintaining long term stability of the DMO output centre frequency in order to ensure maximum photon return efficiency from a sodium LGS it would be necessary to exploit the Doppler linewidth of the mesospheric sodium population optimally to minimise saturation. This would require that the single longitudinal mode output of the CW dye laser display an effective bandwidth on the timescale of the sodium upper level lifetime (16 ns) that represented a significant proportion of the Doppler linewidth. The exact bandwidth necessary for optimum photon return efficiency from a population at a given temperature could be determined

by computer modelling. Work done in this field, both by our colleagues at Imperial College, London, and at other sites suggest that, for a population temperature of 200 K, and in the absence of optical population pumping between hyperfine lower levels, the optimum bandwidth is 600 MHz. This figure of course varies slightly with season (as a result of variation in temperature). Owing to the very low sodium density in the mesosphere (of the order of 10^3 cm^{-3}) and the relatively low temperature collisional redistribution over states is extremely slow and therefore the effects of optical pumping can potentially be very significant, however the small size of the guide star spot and the bulk velocities measured within the sodium layer suggest that this effect may not be so significant. As a results of these two effects it was necessary to design a system incorporating the maximum flexibility in output bandwidth.

The conventional way to achieve this effect is to pass the beam through an electro-optic phase modulator (EOPM) to which one or a number of radio frequency (rf) drive signals are applied. The resultant modulation of refractive index in the medium gives rise to an instantaneous phase modulation of the optical beam and an effective shift in frequency. Accomplishing this on the necessary timescale could potentially give us the effect we needed.

Current commercial electro-optic phase modulators are standing wave devices in which a drive signal consisting of one or a number of discrete rf frequencies is used to generate a standing wave refractive index modulation within the medium. Although this allows an effective broadening of bandwidth to be achieved, precise control of effective lineshape requires an unrealistically large number of drive frequencies, so it is necessary to arrive at a compromise in which lineshape is optimised for a reasonable number of drive frequencies. We have undertaken some computer modelling of the effective line profiles to be achieved under a range of drive conditions, and Figures 1 and 2 illustrate the lineshapes that could result from 5 and 7 drive harmonics (3 and 5 discrete drive frequencies) respectively.

More precise control over output spectrum requires a phase modulator in which the drive signal can be continuously varied in time. This requires a travelling wave phase modulator in which the electrical drive signal passes from the electro-optic medium into a matched impedance, thus preventing reflection and the formation of a standing wave. Although such devices are not yet commercially available, over the last

few months we have been in close communication with an academically based commercial organisation that has been developing a device of this kind. They are confident that a product of this type will be available in the relatively short term and that it should allow us far more precise control of spectral output for reasonable drive requirements.

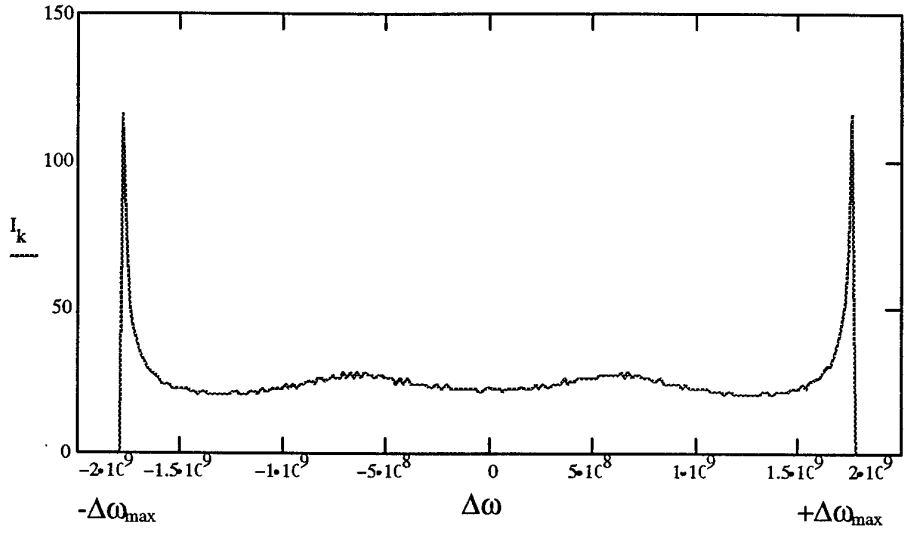

Figure 1

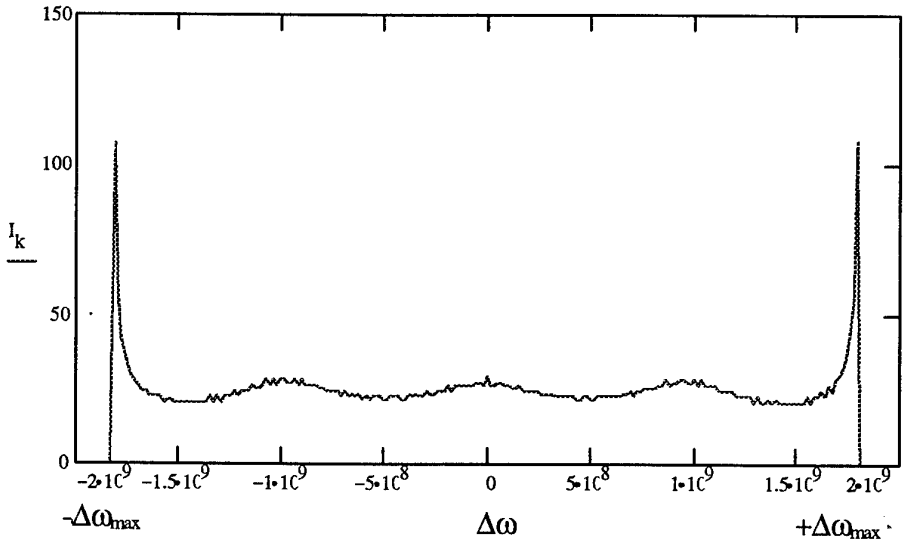

Figure 2

Such a product is not likely to be available for a year or so, however, and consequently, to allow us to pursue our experiments we have purchased a standing

wave EOPM. Although this would not be the device of choice in a final system, it allows us to study the efficiency of pulsed amplification of such a modulated CW signal as well as its effect on spectral distribution, and also compare the results of computer simulation with experimental results.

Pulsed amplification

Once the output of the DMO has been locked to the correct centre frequency and phase modulated to give a broadened effective bandwidth it must be pulse amplified to give the high average power required. In our architecture the average power required from an individual sub-unit is relatively low, as it forms only a part of the overall output power of the system as a whole, however the output power from the DMO is of the order 100-150 mW CW, whereas each sub-unit is expected to contribute around 4-5 W to the system output.

In order to be compatible with our proposed pulse multiplexing strategies it is desirable that the pulsed amplification be accomplished in a double pass arrangement, such that the beam passes through each amplification cell twice, travelling in opposite directions on each transit. As we need to amplify the peak power of our signal from the seed level of around 100-150 mW to a value of 10-15 kW, a gain of 10^5 it is probable that not one but a pair of amplifier cells will be required as the gain medium cannot operate simultaneously in both the exponential gain unsaturated regime and the high pump power conversion efficiency, linear gain regime. The results of the computer modelling work we have performed predicts that it is likely that a pair of amplifier cells will be required, however uncertainties in some of the cross section values mean that it is impossible to be 100% sure until the final experiments have been performed using the DMO we have now constructed.

We have now designed and built a pair of dye cell mounts to take the dye cells we have obtained with a range of dye channel widths. These have now been incorporated into a complete layout incorporating the DMO, including the EOPM (when desired) and atomic sodium frequency-lock, a copper vapour laser (CVL) which we have recently rebuilt to provide the optical pulsed pump power for the pulsed dye amplifiers (PDAs), the beam handling optics and the necessary diagnostics. In addition provision has been made for the incorporation of optical fibre beam delivery of both

DMO output and pump light in place of the current, direct configuration, extending the work on fibre optic delivery already completed.

Conclusions

A CW dye master oscillator (DMO) for use with our proposed scalable sodium LGS system has been constructed. An atomic sodium frequency lock based on polarization spectroscopy has been designed and constructed and has demonstrated its ability to lock the output of the DMO to the required frequency for an extended period of many hours, with precision of ±0.5 MHz. A combination of computer modelling and discussion with manufacturers has enabled us to specify electro-optic phase modulator systems based on both currently available, standing wave technology and travelling wave technology, currently only the subject of research. A suitable standing wave system has therefore been purchased and incorporated into our DMO for evaluation.

The construction of the DMO has therefore been completed, and it has now been fully incorporated into an evaluation system to allow us to study both the output of the EOPM, and the effect of pulsed amplification on spectral content and beam quality. This is to be combined with our investigation into amplifier configurations and amplification efficiency.

It must be stressed that neither the Argon ion laser technology, nor the problems we have encountered associated with it, are intrinsic to our DMO design. Recent progress in diode pumped solid state (DPSS) laser development has yielded devices capable of generating 5 W of CW laser output at 532 nm with high beam quality and low noise. In addition the overall efficiency of such devices is typically over an order of magnitude better than that of equivalent Argon ion lasers, a significant consideration in this application. They are, in addition, more robust and easier to maintain. It is proposed, therefore, that this is the technology that should be employed in any prototype system.

Appendix A

As a result of the general low funding level of the sodium LGS development programme it had seemed expedient to make use of a used Argon ion laser that we were offered. This device contained a failed plasma tube, but was, as far as could be told, otherwise operational.

Part of the funding requested for this work was to allow the purchase of a replacement plasma tube to effect a refurbishment of the laser.

Following the (professional) replacement of the plasma tube the laser operated satisfactorily, giving 5W (all lines) of TEM_{00} CW pump light until the plasma tube failed, possibly as a result of the use of 100% deionised water in the closed loop cooling system when it had been installed. The plasma tube was again professionally replaced and also worked well for a limited time until unsuspected corrosion within the magnet bobbin caused the failure of this plasma tube. Both the plasma tube and the magnet bobbin were again replaced however it then proved to be impossible to obtain TEM_{00} beam mode. Over the following months the laser spent a great deal of time both with the specialist repair company and with their engineers with us. During this time the plasma tube was again replaced (and realigned with the cavity a number of times), as was the entire laser head unit, for (a factory reconditioned) one incorporating an adjustable intracavity aperture. Even this aperture needed replacing as insufficient cleaning had left some oil on its surface which was vaporised and contaminated a plasma tube window and the output coupler.

Design of an atomic Sodium frequency lock for the dye master oscillator of a sodium laser guide star

Summary

An atomic sodium frequency lock has been designed, constructed and evaluated for the long term stabilisation of the output of a continuous wave (CW) dye laser for use as the master oscillator in a scaleable sodium laser guide star (LGS) system for astronomical adaptive optics. The device has demonstrated its ability to lock the laser frequency to the desired point in the sodium D_2 resonance with precision of ± 0.5 Mhz over a period of many hours, without the necessity to introduce a wavelength modulation.

Introduction

It is a fundamental requirement of any design for a sodium layer laser guide star system that the output wavelength be locked in a precise, reproducible and stable manner to the appropriate sodium resonance transition. Only by ensuring this can optimal power coupling from the launched beam into the sodium guide star be maintained.

Such a lock can be accomplished by reference to a wavelength standard in combination with some kind of feedback loop. The wavelength reference may be derived from either a sodium sample, using the wavelength of interest itself, or some secondary standard. To use a transition other than the fundamental sodium one requires either a fortunate wavelength coincidence, or some mechanism by which to use a reference on one line to lock another. Although this latter approach may potentially be accomplished with an acceptable degree of stability and reliability, the use of the transition of interest itself potentially offers greater simplicity and robustness.

There are a number of techniques described in the literature to allow a system such as a dye laser to be locked to an atomic transition, of varying sophistication and precision. All require that a suitable error signal input is available on the device to be locked and exploit one or another physical process to generate such a signal.

Characteristics of frequency locking techniques

All frequency locking techniques require that a sample of the radiation output of the device to be locked passes through a test cell containing a vapour or atomic beam of the appropriate element. Where that element is a solid or liquid at room temperature a heating element will normally be required to raise the vapour pressure to a convenient value.

The beam to be monitored, usually a small proportion of the whole output beam, may make a single pass of the test cell, or may be split into two components to pass through the cell in different directions, usually counter propagating.

Two fundamental properties of a given technique can be used to characterise it. The first is that the wavelength of the tested, or probe, beam may be compared with the full, inhomogeneously broadened linewidth of the transition of interest, the so called Doppler limited techniques, or with the homogeneous linewidth, the Doppler free techniques. It follows that Doppler limited techniques will have lower spectral resolution than the Doppler free ones. In some applications the spectral resolution obtainable from a Doppler limited frequency lock will be sufficient and the lower complexity of such a technique will render it the most appropriate. In many applications, however, a higher precision frequency lock is required, and a Doppler free method must be used.

The second defining characteristic of a frequency lock method concerns the way in which the error signal is generated. In many frequency lock techniques the lock point is defined in terms of a maximum or minimum of the measurement of some physical parameter. Since such a measurement concerns a relative, rather than absolute value, it must be repeatedly compared with neighbouring values to allow the lock to be maintained. In such techniques, therefore, the wavelength of the probe beam must be constantly dithered and the lock error signal used to ensure that the centre point of the modulation remains at the correct wavelength. This modulation is generated by physically moving a mirror within the laser cavity by means of a piezo-electric element. The magnitude of the frequency modulation must be sufficient to give rise to a measurable error signal from the lock feedback loop, and will be directly related to the lineshape in question. In a Doppler limited technique this will naturally

require deeper modulation than in a Doppler free one, however a measurable frequency modulation will always be present on the output of the system.

In many applications such low level frequency modulation are entirely acceptable, however, where this is not the case a non-modulation technique must be used. If no frequency modulation is to be employed then the technique must generate an output signal that gives an unambiguous lock point, combined with an error signal that is not only proportional to frequency offset, but also contains the information as to whether the probe beam is above or below the lock point. In practice this usually means that the lock point generates a zero voltage output and an offset above or below gives rise to a positive or negative error signal. With appropriate conditioning this signal can be input into the dye laser controller to close the feedback loop.

Candidate locking techniques considered

1. Absorption spectroscopy

Conceptually the simplest lock technique employs absorption of the probe beam in the test cell. As a probe beam, close in wavelength to the transition of interest, passes through the atomic vapour in the test cell it will experience a degree of absorption. When it is at the peak of the Doppler line profile the absorption will be at a maximum. If the transmitted intensity is monitored, and sufficient frequency modulation is superimposed for a measurable reduction in absorption to be observed at the two extrema, the modulation drive signal can be combined with the transmission signal to ensure that the modulation remains symmetrical about the line centre.

It can readily be seen that this technique is both Doppler limited and requires modulation of the laser output.

2. Emission spectroscopy

A modification of this technique, though suffering from the same limitations, monitors not the absorption of the probe beam, but the fluorescence emission through a side window of the test cell. In this case a fluorescence maximum is sought rather than a transmission minimum, however the spectral resolution remains the same, and the probe beam must still be modulated.

3. Optogalvanic spectroscopy

A further modification of these simple techniques dispenses with the need for an optical detector and, rather than measuring absorption or emission directly monitors the degree of optical excitation generated by the probe beam by measuring the current flow between a pair of electrodes within the cell. This is a popular technique known as optogalvanic spectroscopy and can provide the basis for a reliable, simple frequency lock, without the difficulties associated with the requirement for optical detectors such as alignment artefacts, differentiating between spectral, spatial and intensity effects, however the spectral resolution is still limited by the Doppler lineshape, and frequency modulation is still required.

4. Saturated absorption spectroscopy

In order to escape the Doppler resolution limitation a number of strategies have been employed. In saturated absorption spectroscopy the sample beam is split into two components: a very low power probe beam, and a relatively higher power pump beam. These two beams exactly counter propagate through the test cell and consequently interact with different velocity classes of atoms, equally but oppositely displaced from line centre. Only when the wavelength exactly coincides with line centre will both beams interact with the same velocity class - that with zero axial velocity. At this wavelength the pump beam will experience a local minimum in absorption as the pump beam reduces the ground state density. Once again, however, although this technique allows Doppler free spectral resolution, a frequency modulation is required in order to ensure that the absorption minimum is maintained.

5. Zeeman spectroscopy

A technique that avoids the necessity for modulation exploits the circular dichroism generated by Zeeman splitting in an atomic population in a magnetic field, longitudinal with respect to the direction of beam propagation. Selection rules mean that the angular momentum associated with circularly polarised light constrains it to interact with transitions corresponding to $\Delta m_l = \pm 1$. For each Zeeman lower level, therefore, the two circular polarizations will give rise to a pair of transitions with

separation proportional to the magnetic field strength. Careful choice of magnetic field can allow the two line profiles to overlap, such that they cross at a point of maximum gradient and this can be used to define a lock point. Although the lineshape in question remains that of the Doppler profile, the change in gradient around this lock point is considerably more rapid than at the peak of an equivalent Gaussian, and consequently the spectral resolution is considerably greater than that of conventional Doppler limited techniques. In addition, since the lock point is defined as that at which the intensity in the two circular polarizations is equal, compared either sequentially or simultaneously, no frequency modulation is required, and offset from the lock point can be determined unambiguously from the relative magnitude of the two signals. The differential signal between the two polarizations yields a zero at the lock point, with a positive signal for one offset, and a negative one for the other.

6. Polarization spectroscopy

Finally there is one technique which combines the benefits of a non modulation method with the spectral resolution of a Doppler free one, and it is this one that we have chosen to study and will be described below. It has been termed polarization spectroscopy.

Theory of Doppler Free Techniques

If a low power optical beam is allowed to pass through a cell containing a low pressure of sodium vapour, and is then tuned in wavelength through a resonance line, then as the peak of the line is approached increasing absorption of the beam will occur, resulting in excitation of sodium atoms and reduction in the transmitted intensity. Interaction will occur first with highly Doppler shifted atoms, but as the frequency approaches line centre the velocity class of interaction will have lower and lower velocity component in the direction of beam propagation until, at Doppler line centre, the beam will be interacting with zero velocity class. Beyond this the beam will tune through the velocity class with opposite direction with respect to the beam.

If a small part of this pump beam is split off and caused to pass through the test cell, precisely counter-propagating with the original beam, then tuning through the Doppler line profile will cause each beam to interact independently with classes of

atoms with equal, but opposite velocity until they lie within the homogeneous linewidth of the line centre. At this point both beams will be interacting with the same group of atoms. The depletion of the ground state population by the (higher power) pump beam will therefore cause a reduction in absorption of the (low power) probe beam. As the wavelength of the beams is scanned across the full Doppler linewidth of the transition the absorption of the probe beam will be seen to experience a local minimum over this region, the Lamb Dip. This is the basis of the Doppler free Saturated Absorption Spectroscopy technique, however, as mentioned above, modulation of wavelength is required to ensure that the centre of the Lamb Dip is retained.

Instead of merely using absorption, and hence transmitted intensity of the probe beam, as the discriminating factor however, the birefringence and dichroism associated with beams of defined polarization can be used to allow spectral position to be defined without the necessity for modulation, and this is the basis of the Polarization Spectroscopy technique.

A number of variations of the basic Polarization Spectroscopy technique have been presented in the literature since the original paper in 1976 [Wieman and Hänsch, 1976], including [Kim *et al.*, 1988] and [Thomsen *et al.*, 1995]. It is upon this latter variation that we have based our study.

The use of a linearly polarised pump beam imposes a quantization axis upon the magnetic hyperfine levels, which gives rise to both polarization dependent absorption (dichroism) and refractive index (birefringence). The use of a circularly polarised probe beam, and its subsequent resolution into two, orthogonal, linear polarization components, rotated ±45° with respect to the pump beam polarization, allows the extent of these effects to be measured. By choosing the desired operating point to be one at which the transmitted amplitude of these two components is to be equal allows for a lock point that is unambiguous, requires no frequency modulation and is relatively independent of total beam intensity.

Experimental

Figure 1 illustrates the key elements of our system, which can also be seen in the colour photograph attatched.

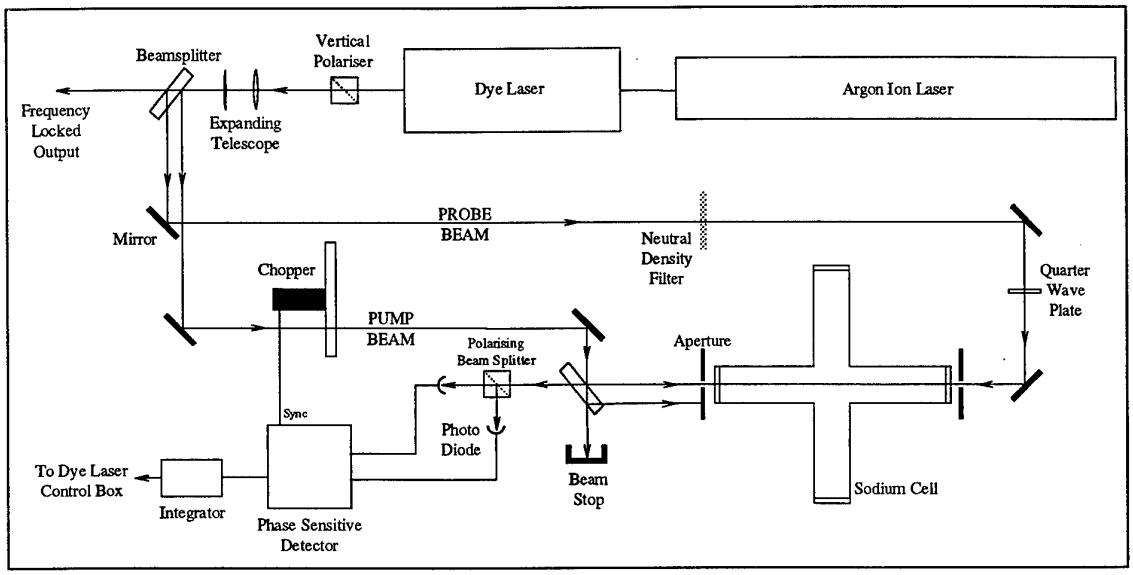

Figure 1

The Argon Ion laser was a Spectra Physics Model 165 5W (all lines) device, and this was used to pump Coherent Model 599-21 standing wave CW dye laser.

The output polarization state of the dye laser is imposed by its intra-cavity components, including a Brewster angle birefringent filter, however, to ensure maximum polarization purity, and extra-cavity polarizer cube has also been incorporated, rendering the beam highly linearly polarised in the vertical direction (>99.9%). A beam expanding telescope was incorporated, giving a magnification of 2× in order to reduce the (nearly diffraction limited) divergence of the beam over the relatively long beam path through our current (breadboard) system layout.

An uncoated, 15 mm thick silica flat was used to sample the output beam from the dye laser, the front and back faces being used to generate the pump and probe beams respectively. Following separation of the pump and probe beams the intensity of the probe beam was reduced further by a neutral density (ND) filter (OD = 0.3). The pump beam retained its vertical polarization, and was deflected by a second uncoated silica flat through the atomic sodium cell. The probe beam passed through a quarter wave plate, with its optic axis at 45° to the direction of polarization, rendering

the output circularly polarised, before being deflected though the atomic sodium cell in the opposite direction to the pump beam. A pair of iris apertures were used to further define beam position and diameter, and assist alignment.

The sodium cell was constructed in house to allow maximum flexibility in design and consisted of a cruciform layout with four arms in the horizontal plane, of approximately 15cm length, with a silica flat mounted at the end. An arm pointing vertically downwards contained an ampule containing 1g of pure sodium metal, which was wound with resistance wire to form a heater element. A vertical arm pointing upwards made connection to the gas handling components, including rotary vacuum pump via liquid nitrogen trap, Pirani gauge and helium gas line. These dimensions were sufficient to give rise to negligible contamination of the windows.

Once the probe beam had passed through the test cell it is passed through a further polarizer, set at 45° to the vertical, in order to analyse the relative magnitude of the polarization components at + 45° and - 45° with respect to the pump beam polarization, thus measuring the combined effect of the birefringence and dichroism generated by the pump beam. The use of a circularly polarised probe beam allowed these two components to be monitored simultaneously by a pair of matched photodiodes.

It can be shown [Thomsen, 1995] that the transmission intensity of the probe beam through a polariser, rotated by θ° with respect to the polarization direction of the pump beam, for an optically thin medium, is given by:

$$I(\theta) = \frac{I}{2}\left(1 - \frac{\alpha_{\parallel} + \alpha_{\perp}}{2} L - \frac{L}{2}\Delta\alpha\cos(2\theta) - \frac{\omega L}{c}\Delta n \sin(2\theta)\right)$$

where I is the probe beam intensity, $\Delta\alpha = \alpha_{\parallel} - \alpha_{\perp}$ and $\Delta n = n_{\parallel} - n_{\perp}$ and L is the absorption path length.

By measuring the difference in intensity between $I(45°)$ and $I(-45°)$ as the wavelength of the beam is scanned through a single hyperfine transition, a dispersion curve can be obtained which has the desirable characteristic of passing through zero at the peak of the transition. It is this characteristic that allows the technique to be used in the absence of frequency modulation as not only does an equal signal from the two photodiodes indicate that the transition peak has been attained, but also the direction of any offset from the peak can be unambiguously determined by which channel is the

greater. Figure 2 illustrates a typical dispersion signal obtained from our system. The frequency offset values are with respect to the sodium D_2 $3S_{1/2}$ F=2 to $3P_{3/2}$ F=3 hyperfine transition (at 0 MHz).

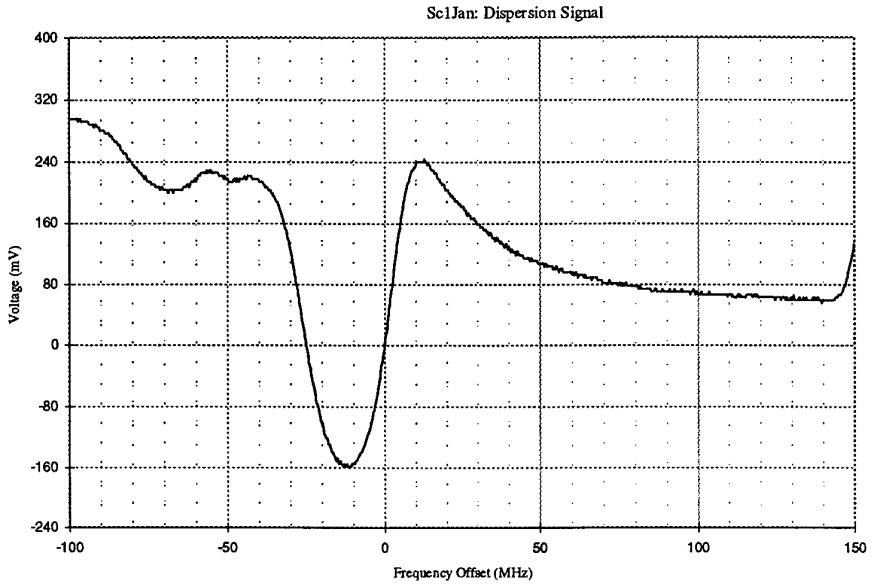

Figure 2

In order to allow the subtraction of any background signal the pump beam path incorporated a beam chopper, and the outputs of the two photodiodes measuring $I(45°)$ and $I(-45°)$ were fed into the differential inputs of a digital phase sensitive detector (PSD), while the reference signal from the chopper was fed to the sync input.

A simple integrator unit followed the output of the PSD in order to suppress oscillation in the laser output frequency as a result of overshoot, and also incorporated an adder to allow a small frequency offset from the peak of the transition to be readily incorporated.

It is important to match the output error signal from the frequency lock, in terms of volts per MHz, with the input offset signal scaling of the dye laser controller. In addition, the error signal must retain this calibration independently of fluctuations in laser output power. In order to do this a third photodiode was used to monitor a sample of the probe beam taken from a back reflection from the ND filter. The output of this was scaled using a transimpedance amplifier with an adjustable gain stage and

fed into a normalisation input of the PSD. Both the gain of this, and the scan width set on the dye laser controller could be adjusted to ensure good matching.

Minor adjustment of the operating point, with respect to the peak of the chosen hyperfine transition could be made by slight rotation of the quarter wave plate in the probe beam arm, imposing a very slight degree of ellipticity to the polarization. The effect of this procedure on the dispersion curve for a range of rotation angles has been plotted in Figure 3. This procedure allowed us to shift the profile of the dispersion curve to maximise the robustness of the technique against frequency jumps by placing the operating point as nearly as possible at the centre of a symmetrical gradient.

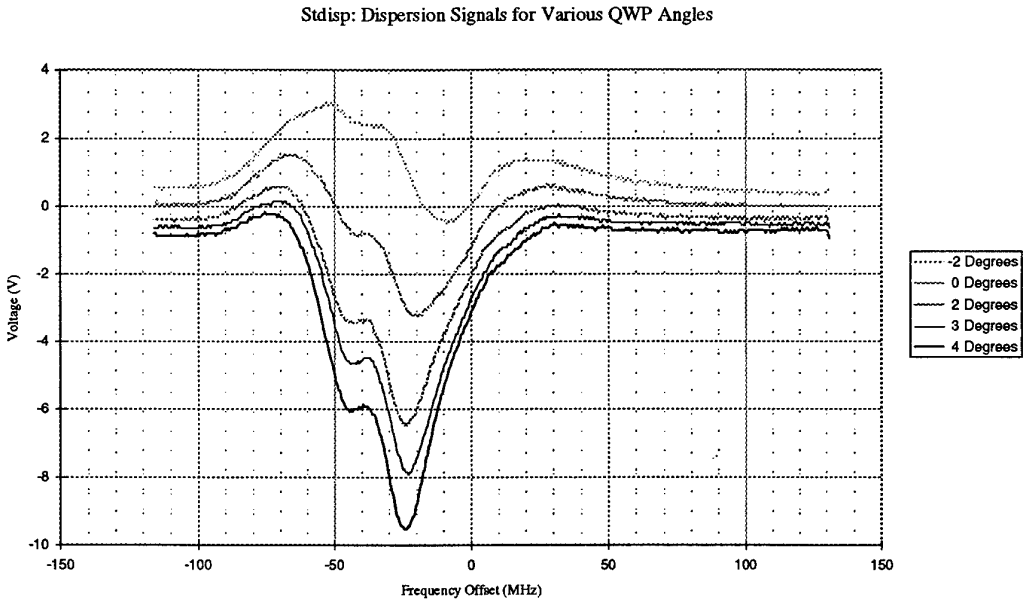

Figure 3

Results

Figure 4 is a plot of the stabilisation signal from the sodium lock with the laser running open loop (with only its internal, temperature stabilised cavity based frequency lock) over a period of 30 minutes. The correction signal (in mV) can be converted to a frequency drift with a scaling of 40 mV/MHz, however the roll over at 15 mins corresponds not to a reversal of the drift but the point at which the correction dispersion curve reverses. This drift, then, lies within the figure specified for the dye

laser of 100 MHz/hour which is, however, unacceptable over the period of an extended run of operation of perhaps 8 hours or more.

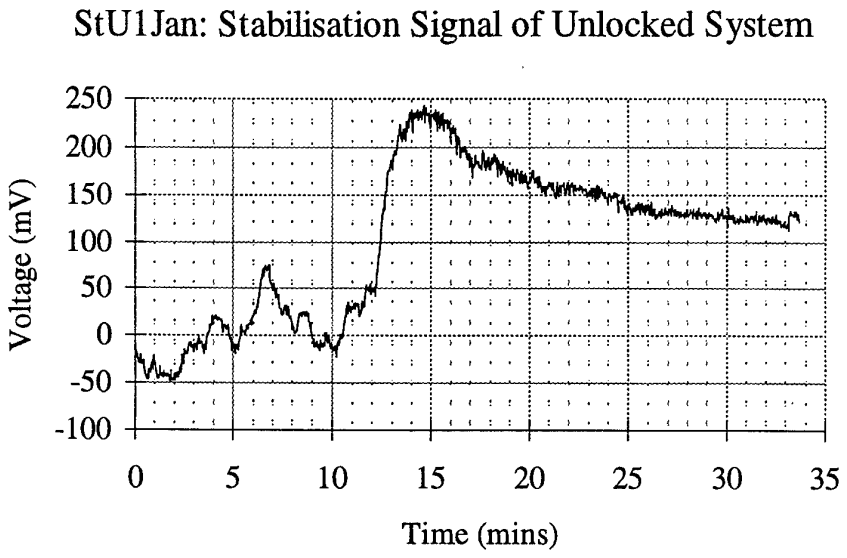

Figure 4

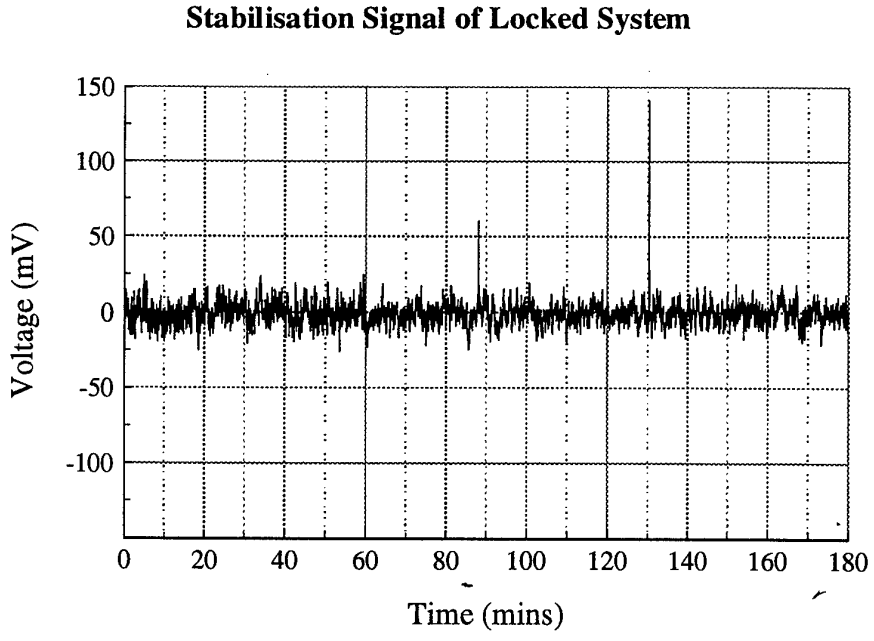

Figure 5

Figure 5 is a plot of the stabilisation signal with the system lock loop closed, over a period of 3 hours. The action of the lock in maintaining the centre frequency over this period to within ±0.5 MHz may clearly be seen, as can two occasions where an acute frequency jump, probably as a result of a bubble in the dye jet, was immediately rectified.

An extended run of 7 hrs 30 minutes has also been made, and during that time the laser again remained locked to within ± 0.5 MHz over the full period.

Conclusions

Our implementation of the Polarization Spectroscopy technique has been demonstrated to lock the wavelength of the dye laser to high precision over a period of 7 hr 30 mins. This technique appears to offer an attractive combination of high precision, robust operation combined with no requirement for modulation of the laser wavelength.

Our set-up was relatively large and slightly cumbersome, in the nature of a breadboard, experimental, prototype system. This was to allow flexibility for optimisation, however we now feel that a suitable system might now be constructed considerably more simply by replacing our sodium cell, vacuum pump, liquid nitrogen trap, Pirani gauge and gas and vacuum lines with a simple, sealed off, low pressure cell, made of sodium resistant glass. If this were found to be so, and the operational lifetime were found to be acceptable, then this could represent a significant further improvement on the system.

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